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The Effect of Agricultural Waste as a Filler in Fibre Cement Board Reinforced with Natural Cellulosic Fibres

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***Abstract*—**This investigation aims to characterize the effect of corncob (CC), an agricultural waste, for potential use as a filler material, reducing cement in natural fibre-reinforced cement composite boards used for building applications in low-cost housing estates in developing countries. The CC is readily and abundantly available in many West African States. However, this agricultural waste product has not been put to any effective use. Hence, the objective of the current research is to convert this massive agro-waste resource into a potential material for use as filler materials reducing cement contents in fibre-cement board production. Kraft pulp fibre-reinforced cement composite boards were developed with the incorporation of the CC powder at varying percentages of 1-4% as filler materials to reduce the cement content, using a laboratory-simulated vacuum de-watering process. The mechanical properties of the developed cement boards were characterized through a three-point bending test, while the fractured morphology of the cement boards was examined through a Scanning Electron Microscope (SEM). Results revealed that the flexural strength of the composite board improved significantly with an optimum enhancement of 39% when compared to the reference sample without CC replacement, however, the flexural behaviour (ductility) of the composite board was slightly affected by the addition of the CC powder at higher percentage. SEM observation of the fractured surfaces revealed good bonding at the fibre-matrix interface as well as a ductile-to-brittle fracture mechanism. Overall, the composite board incorporated with 2% CC powder as filler materials had the optimum properties, satisfying the minimum requirements of relevant standards for fibre cement flat sheets.

***Keywords*—**Kraft pulp fibre, fibre-cement board, agricultural waste, sustainability, building applications.

I. Introduction

THE carbon footprint and the energy consumption of the building and construction industries remain a global challenge requiring the combined efforts of researchers, academia, industry stakeholders, and governmental and non-governmental organisations to harmonize ideas and provide a sustainable solution to this problem [1]-[6]. Although the efforts of several researchers [7]-[18] have yielded some progressive results, there are still areas requiring sustainable solutions.

In recent years, the agricultural sector has been seen as a progressive and promising sector offering sustainable solutions through the integration of its massively generated sector-waste products into different industries, thereby, producing new and environmentally friendly products that are sustainable, renewable, and capable of reducing the carbon footprint of building and construction materials [19]-[25]. Despite these promissory projections, the amount of waste generated annually from the agricultural sector, particularly in developing countries continues to have a negative impact on the environment and the eco-system at large [6], [26], [27]. Many researchers [14], [28]-[31] have explored different agricultural waste products such as sunflower ash [29], CC ash [32]-[36], rice husk ash [37], and wood bottom ash [38]-[40], etc., either as partial replacements for cement or as filler materials in cement-based composite materials.

According to Owolabi et al. [41], CC is the agricultural by-product obtained from corn or maize, it is the cylindrical, hard-thick central core on which are borne the grains or kernels of corn, normally aligned in rows. In most cases, the CC ash is usually obtained by burning the agro-waste product (CC) to ashes in a controlled environment, typically within the temperature range of 500-700 °C [14], [29], [35]. The use of CC ash as partial cement replacement in cementitious-based composite materials and/or concrete has been investigated by a number of researchers [34], [36], [41]-[44]. For instance, Adesanya and Raheem [32] developed CC ash blended cement composites using the CC ash as a pozzolanic material by applying 0-25% by weight of the matrix material. The authors reported that the developed CC ash blended cement composites satisfied the requirements of relevant standards such as ASTM C150 [45]. Furthermore, they concluded in their study that all the CC ash blended cement has a higher setting time than the reference sample and therefore, they are mostly applicable in areas where there is a low rate of heat development for example in mass concreting. They suggested that the optimum blending proportion for the CC ash should not exceed 15%. In another study by Akindahunsi et al. [35], the performance of CC ash in cement mortars was evaluated, and the researchers reported an improvement in the mechanical (flexural and compressive) properties of the cement mortars containing CC ash. They concluded that the cement mortar containing 10% CC ash

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blended with cement recorded the optimum results in all the properties studied. Shakouri et al. [46], on the other hand, perceived a different view regarding the incorporation of CC ash into cement-based materials perhaps due to the outcome of their study. The authors incorporated 3% and 20% CC ash by mass of cement and reported that the inclusion of the CC ash significantly accelerated the cement hydration process. Hence, the resulting concrete composite recorded a significantly lower compressive strength and bulk resistivity. Consequently, the authors suggested that CC ash should not be regarded as a feasible pozzolanic material but may be useable as filler materials in concrete composite for low-strength applications.

From the foregoing, it can be seen that a larger percentage of the available literature on the use of CC in cement-based materials generally employed this agro-waste product in its ash form (i.e., CC ash). Furthermore, some levels of discrepancies have also been noticed in some of the results reported which may be due to the variation in corn species and the farming regime in different locations. Therefore, the current research opted for using the CC in its original form without turning it into ash and studying its effect on the mechanical and microstructural properties of cement-based composite boards reinforced with kraft pulp fibres obtained from recycled waste cardboard papers. Furthermore, this study aims to blend waste materials from different sources into composite boards in an attempt to reduce materials costs without compromising mechanical performance.

II. Materials and Methods

A. Materials

The following materials were used for this research: Kraft pulp fibres were obtained mainly from waste brown cardboard papers collected from stationaries and mail stores around Cranfield University, Cranfield United Kingdom, with its photographic and SEM images displayed in Figs. 1 (a) and (b). Fisher Scientific Ltd., UK supplied general purpose grade CC powder, with its photographic and SEM images displayed in Figs. 2 (a) and (b) while its master sizer particle size analysis is presented in Fig. 3. Ordinary Portland Cement (OPC) HS 52 BSEN 197-1 BSEN I 52.5 N was supplied by Hanson Heidelberg Cement Group, Maidenhead, England. The camera photo, electron image, and elemental composition (SEM-EDS) of the OPC are presented in Figs. 4 (a), 4 (b) and 5, respectively. The conical flask, vacuum pump, rectangular steel mould, rubber bung, hose and other items required to successfully mimic the Hatschek method in the laboratory were supplied internally by the Composite and Advanced Materials Centre, Cranfield University, United Kingdom.

B. Methods

Waste Kraft Fiber Production

To begin with, the waste cardboard papers were shredded manually into smaller pieces with the aid of scissors while removing all the foreign materials such as glue and pins from the shredded pieces. After that, the carton papers were soaked in clean water for 48 hours in the laboratory, applying a 5:1 water-to-cardboard weight ratio. The soaked carton paper was then continuously agitated for 2 hours in the laboratory as depicted in Fig. 6. Next, the product from the agitation process was further pulverized in a table-top blender at a low speed for a further 8-10 minutes. The product obtained from the blender was manually drained of the water used for the pulping process. The final product was stored in zip bags and kept in the freezer at 3 ± 1 °C. The average moisture content of the kraft pulp fibre was 70%. Fig. 6 demonstrates a pictorial representation of the production technique employed for producing the kraft pulp fibre.

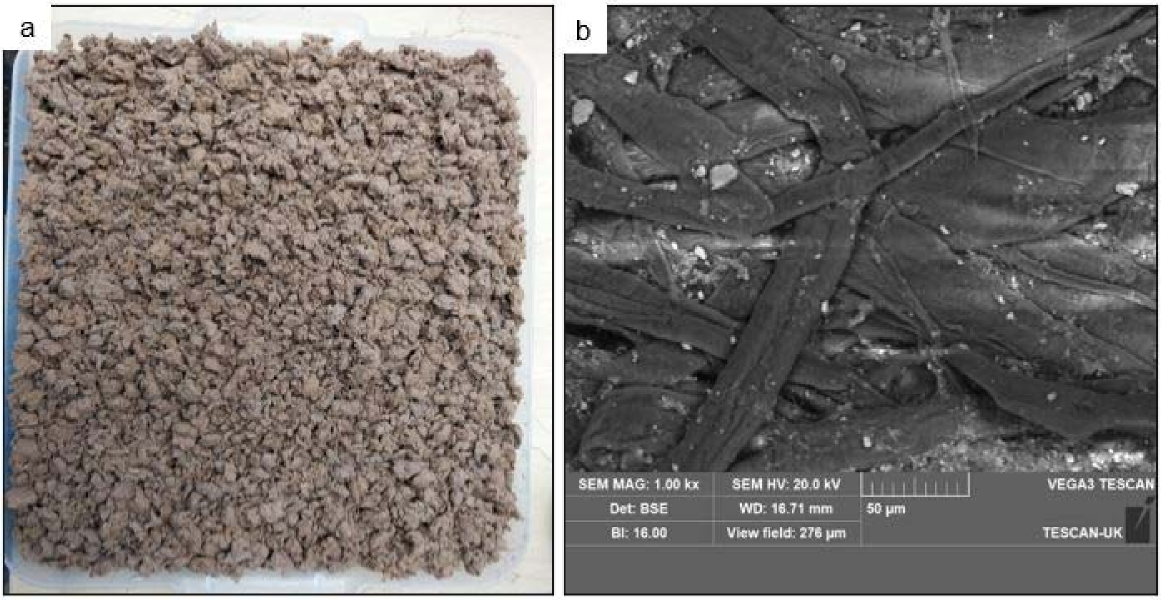


Fig. 1 Kraft Pulp Fibre: (a) Camera Photo (b) SEM Image

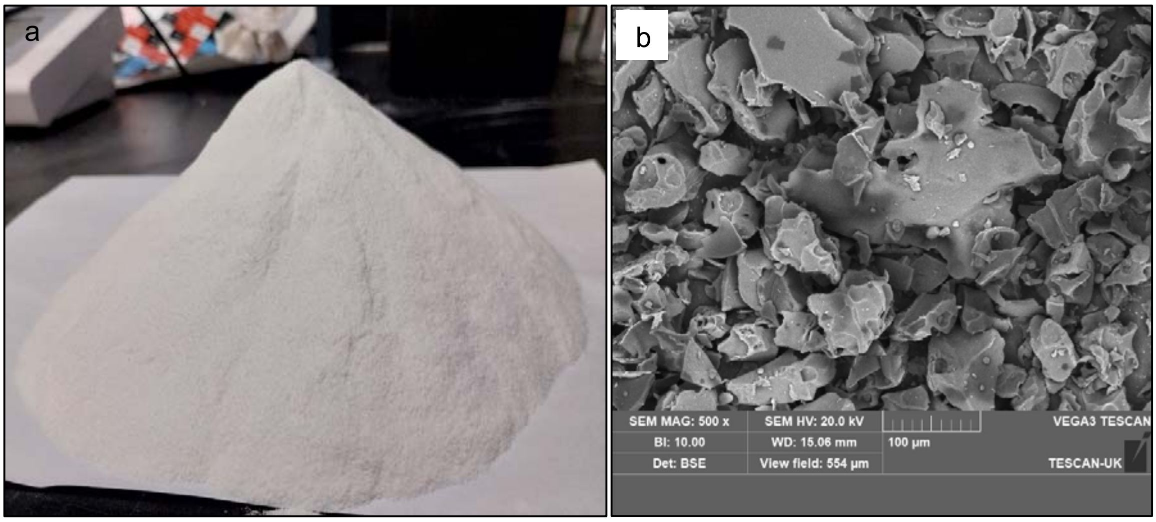


Fig. 2 CC Powder: (a) Camera Photo (b) SEM Image

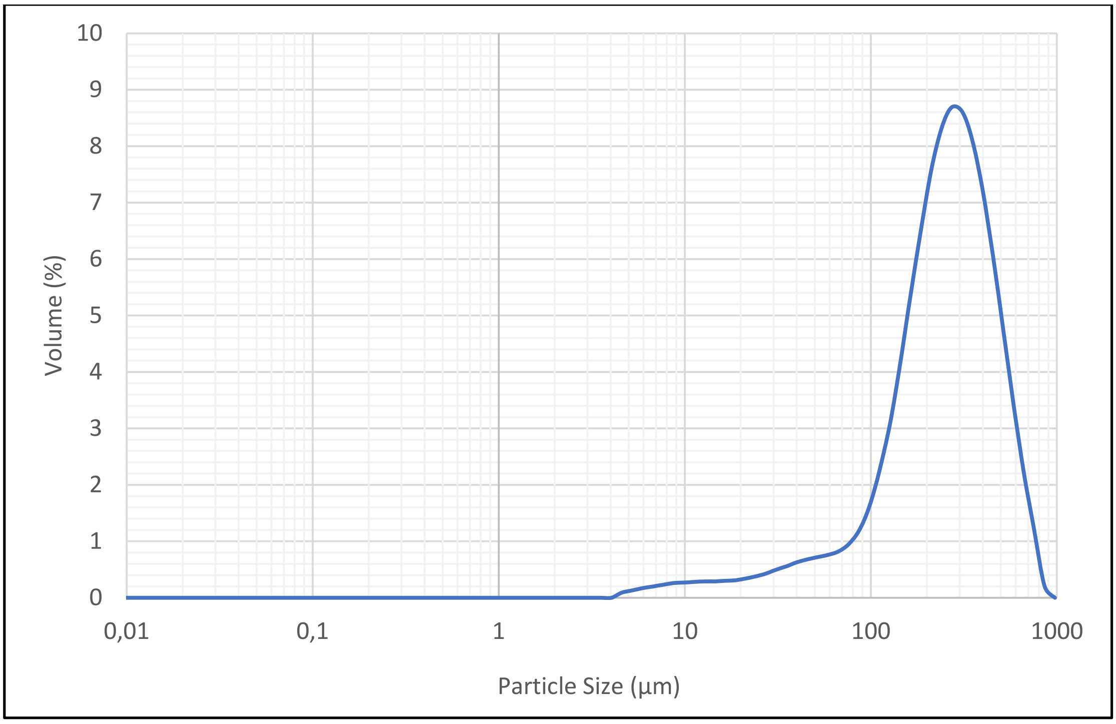


Fig. 3 Master Sizer Particle Size Analysis of CC Powder

Production of Kraft Pulp Fiber Reinforced Cement Composite Boards Incorporating CC as Filler Material

The process of composite manufacture was carried out using the guidelines provided in [4]. Using a compact handheld mixer set to spin at 600-1900 rpm, 750 ml of water and a known weight of kraft pulp fibre were first mixed thoroughly for about 5 minutes. This guarantees that fibres from the kraft pulp are dispersed evenly throughout the water. After that, the kraft pulp mixture was vigorously mixed for a further 5 minutes to achieve homogeneity. Next, a specific amount of cement matrix was added, and the CC powder was also introduced in the appropriate amount as detailed in Table I. Following mixing, the resultant slurry was gradually poured into the 180 mm by 80 mm rectangular steel mould which has been pre-assembled as shown in Fig. 7 (a). The vacuum pump that was attached to the mould was used to extract the excess water from the mixed slurry. One end of the mould had a conical flask connected to it, which was used to collect the excess water. Any leftover water that might have become trapped in the now-thickened slurry was pushed out of the specimen by compressing it uniformly with a weight of 12 kg while keeping the vacuum pump operating. After running the vacuum pump for a further 2-3 minutes, the sample was carefully demoulded onto a levelled rectangular surface. Following a 15-20-minute exposure to the air in the laboratory, the specimen was thereafter placed in a high-humidity chamber to complete the curing process for 7 days, 14 days, and 28 days. The high-humidity curing chamber was maintained at a constant temperature of 25 ± 2 °C and 95% relative humidity to ensure that the cement hydration process was completed. After curing the samples for the required number of days, their flexural performance was assessed following the BS EN 12467 standard [47]. 15 specimens were made for each sample code; five were tested after 7 days, five after 14 days, and the remaining five after 28 days of hydration. Each specimen has a thickness ranging from 8 mm and 10 mm. A selection of fibre cement board specimens produced via the lab-based vacuum de-watering process is shown in Fig. 7 (b).

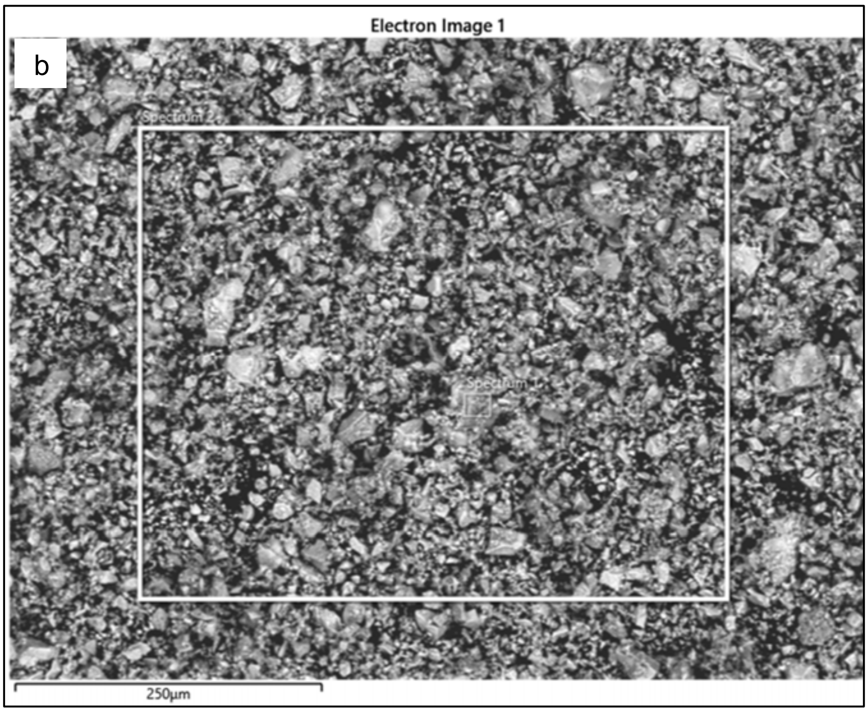
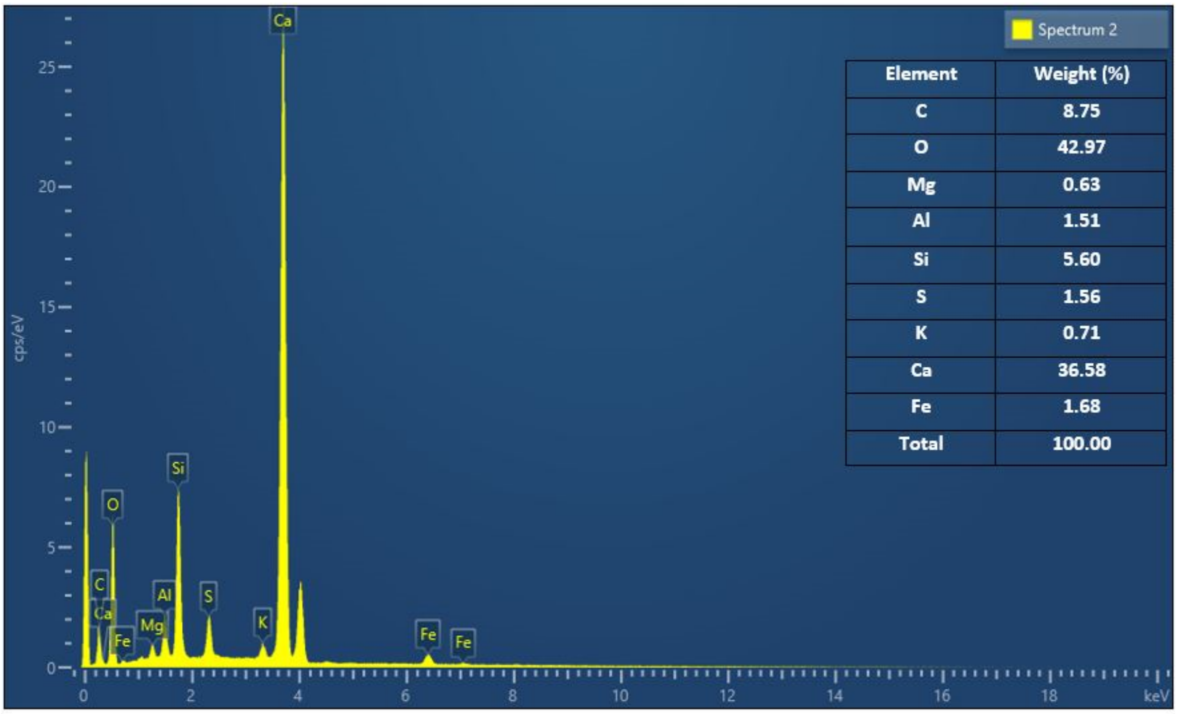


Fig. 4 OPC Particles: (a) Camera Photo (b) SEM Electron Image



Element	Weight (%)
C	8.75
O	42.97
Mg	0.63
Al	1.51
Si	5.60
S	1.56
K	0.71
Ca	36.58
Fe	1.68
Total	100.00

Fig. 5 EDS Analysis of OPC Particles

Fig. 6 Camera Photo Explaining the Steps Involved in Producing the Kraft Pulp Fibre

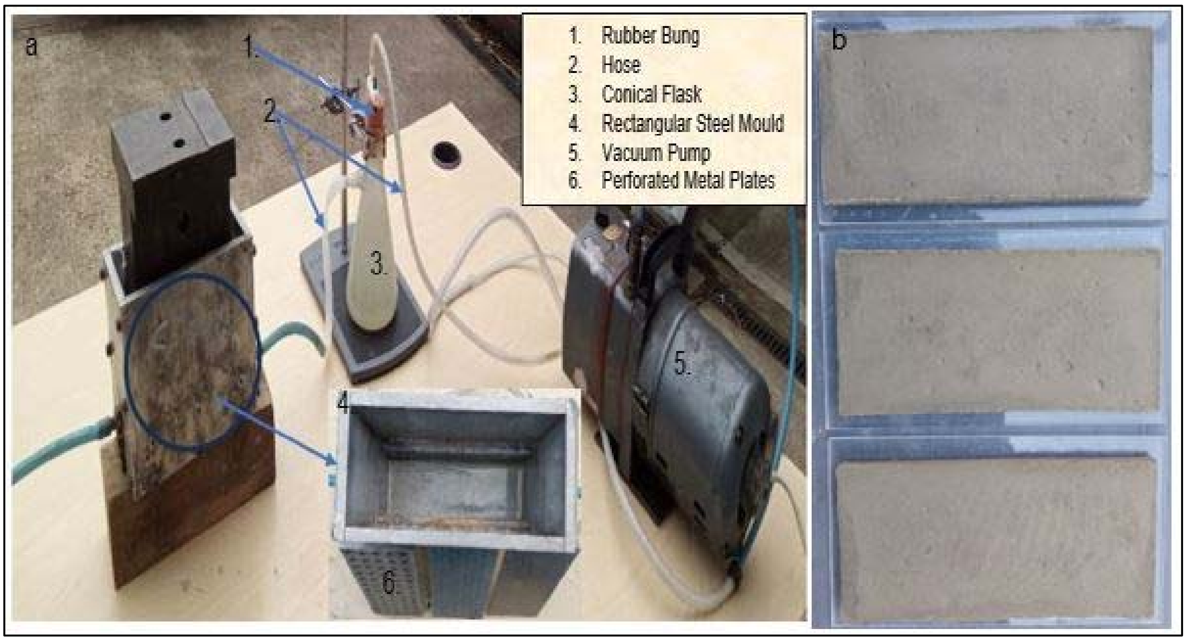


Fig. 7 (a) Laboratory Set-up for Composite Production (b) Selection of Manufactured Specimens in the Lab

C. Mechanical Properties Test

The manufactured cement composite boards were subjected to mechanical properties test (flexural strength and flexural behaviour) through bending, using an Instron 4467 electromechanical testing machine following BS EN 12467 standard. The 7-day, 14-day, and 28-day cured specimens were simply supported on the testing machine using two supports having a radius rounded to 20 mm each. The distance between the two supports was fixed and maintained at 125 mm throughout the test. By following the standard, the individual specimen was tested to fracture within a time frame of 10-30 seconds by applying a crosshead speed of 5 mm/min. The flexural strength of the cement composite board is known as the modulus of rupture (MOR), and it is calculated by applying the formulation of (1):

$$MOR = \frac{3FL_s}{2be^2} \quad (1)$$

where F = breaking load (N); L_s = span between the axes of the supports (mm); b = width of the specimen (mm); e = thickness of the specimen (mm).

TABLE I
MIX DESIGN FOR COMPOSITE DEVELOPMENT

S/N	Sample Code	Cement Matrix (g)	Kraft Pulp Fibre (K) (g)	CC Powder (g)
Stage 1 (Cement and Kraft pulp fibre)				
1	Control	200	0	0
2	K4	192	8	0
3	K6	188	12	0
4	K8	184	16	0
5	K10	180	20	0
6	K15	170	30	0
7	K20	160	40	0
Stage 2 (Cement, Kraft pulp fibre and CC)				
8	K10-CC1	178.2	20	1.8
9	K10-CC2	176.4	20	3.6
10	K10-CC3	174.6	20	5.4
11	K10-CC4	172.8	20	7.2

D. Morphological Examination of the Fractured Samples Using SEM

The fracture mechanism and the filler material interaction within the composite boards were studied on the fractured surfaces of the kraft pulp fibre-reinforced cement board specimens by employing a SEM, Tescan VEGA 3 equipped with an Oxford instrument detector. All fractured samples were inspected using the low vacuum mode to reduce specimen charging and improve conductivity for better imaging.

III. RESULTS AND DISCUSSION

A. Evaluation of the Flexural Performance of FCB Reinforced with Kraft Pulp Fibre

The results of the flexural strength of the kraft pulp fibre-reinforced cement composite boards are presented in Fig. 8. It was observed that the flexural strength of the composite boards increases with the introduction of the kraft pulp fibre as reinforcement. Furthermore, it can be seen that as the kraft pulp fibre content increases, the flexural strength of the composite boards increases gradually up to a maximum of 10 wt.% kraft pulp fibre reinforcement content. Beyond this point, the composite boards begin to experience a gradual reduction in flexural strength, perhaps due to the introduction of excess kraft pulp fibre (at 15 wt.% and 20 wt.%) which may have constituted weak points within the composite board leading to the observed reduction in strength. Moreover, it was observed that as the period of hydration increases from 7 days to 28 days, the flexural strength of the composite boards increases for all composite samples. This could be attributed to the cementitious curing process which continues to produce cement hydration products as the period of hydration increases. It was further noted that the addition of the kraft pulp fibre increases the flexural strength of the composite boards significantly achieving an optimum value of 7.68 MPa and 8.01 MPa at 7 days and 28 days of hydration respectively for composite board reinforced with 10 wt.% kraft pulp fibre. When this is compared to the control sample with a value of 4.64 MPa and 5.45 MPa at 7 days and 28 days of hydration respectively, a 65% and 47% enhancement in strength was achieved in the composite board containing 10 wt.% kraft pulp fibre as reinforcement. Khorami and Ganjian [48] reported a similar level of enhancement in strength in their study on the production of cement composite boards using cellulose fibre.

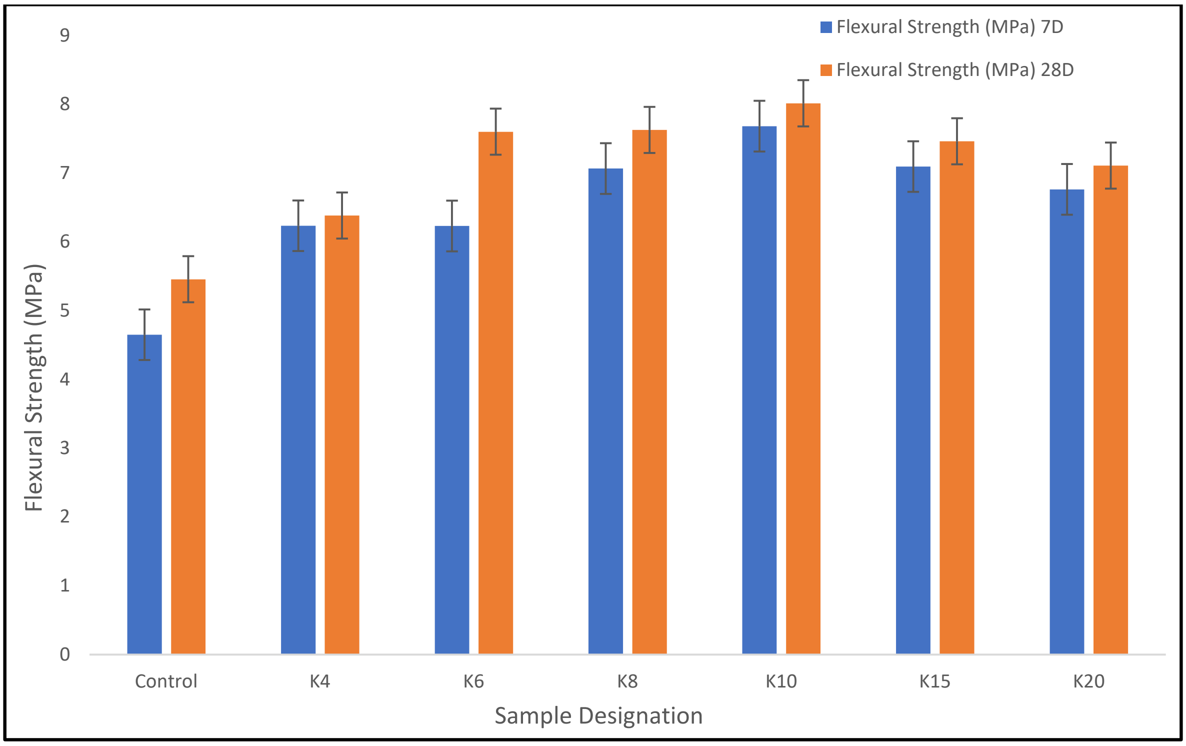


Fig. 8 Flexural Strength of FCB Reinforced with Kraft Pulp Fibre (7 & 28 Days)

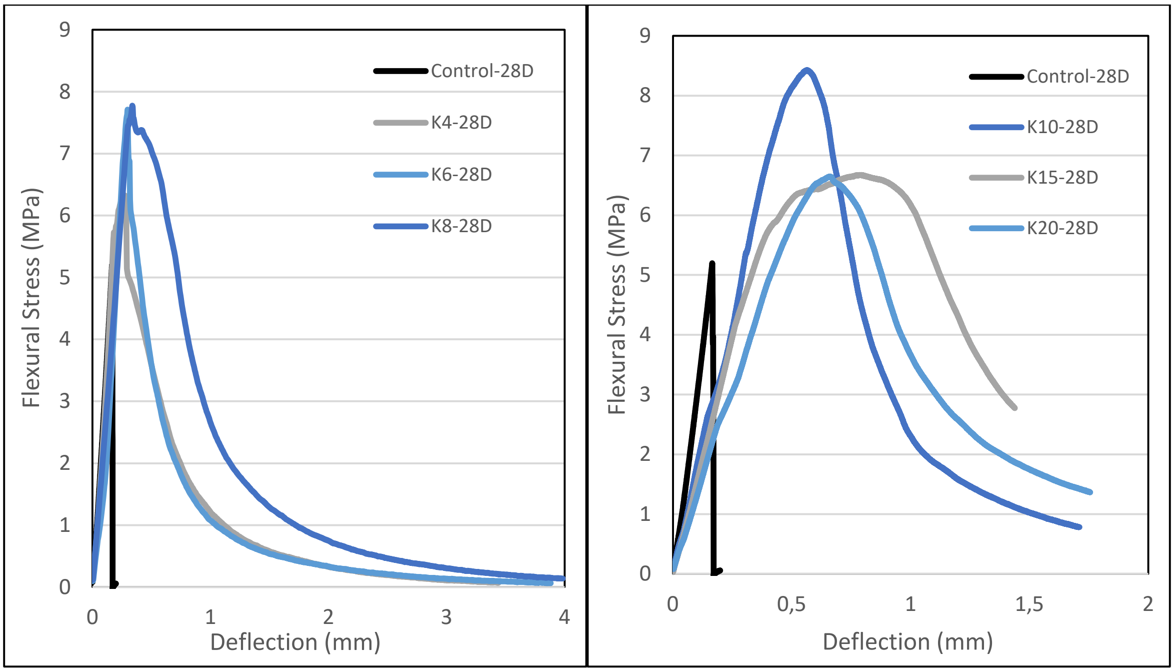


Fig. 9 Flexural Behaviour of FCB Reinforced with Kraft Pulp Fibre (28 Days)

Fig. 9 shows the flexural response of the composite boards under a three-point loading condition. Firstly, it was observed that the control sample which contains cement matrix only without any fibre reinforcement failed suddenly, displaying the brittle fracture characteristics of the cementitious matrix, peaking at approximately 0.2 mm deflection. On the other hand, all the composite samples reinforced with 4-8 wt.% kraft pulp fibre show a slightly higher deflection response peaking at approximately 0.5 mm. Furthermore, it was observed that for all the composite samples reinforced with 10-20 wt.% kraft pulp fibre, a much higher deflection response was noticed. This could imply that as the kraft pulp fibre reinforcement content increases, the ductility as well as the flexural behaviour of the composite boards increases. This shows that the presence of the kraft pulp fibre reduces the brittleness in the composite boards thereby impacting a substantial level of flexibility in the composite samples, allowing the composite boards to support further loading beyond the initiation of first cracks. From the foregoing, it can be seen that the composite board containing 10 wt.% kraft pulp fibre as reinforcement shows the highest flexural strength with considerably good ductility. Therefore, this composite sample (K10-28D) was selected for further study in the next stage of the research.

B. Evaluation of the Flexural Performance of FCB Reinforced with Kraft Pulp Fibre Incorporating CC Powder as Filler Material

The flexural strength of cement composite boards reinforced with 10 wt.% kraft pulp fibre and incorporating 1-4% of CC powder as filler material is presented in Fig. 10. Firstly, it was observed that the flexural strength of all the composite boards continues to increase as the number of hydration days increases from 7 days to 14 days, and then to 28 days. This is due to the continuous formation of cement hydration products as the number of hydration days increases. Furthermore, it can be seen from the graph that the incorporation of the CC powder as filler material increased the flexural strength of the composite boards significantly at lower percentage levels (1-2%), resulting in an overall enhancement of 10% and 29% in composite sample K10-CC1, and 17% and 39% in composite sample K10-CC2 respectively at 7 days and 28 days when compared to the reference composite sample K10. This could imply that at a lower percentage of 1-2%, the CC powder was able to perform its role as a filler material by filling the voids within the composite boards thereby increasing the particle packing within the composite boards, leading to the observed increase in flexural strength at this percentage levels. However, when the percentage of CC as filler material was increased to 3% and 4%, the flexural strength of the composite boards dropped drastically, first at early ages and then at later ages. This could be due to the CC powder interfering in the fibre-matrix interface leading to a reduction in the interaction between the reinforcing kraft pulp fibre and the cementitious matrix. This reduction in the interaction at the fibre-matrix interface led to the formation of weak bonds between the cement matrix and the reinforcing fibres resulting in lower mechanical strength as observed in the composite samples K10-CC3 and K10-CC4.

Fig. 11 presents the flexural behaviour of composite boards containing 10 wt.% kraft pulp fibre and 1-4% of CC powder as filler materials. Firstly, it was observed that the incorporation of CC powder as a filler material contributed to enhancing the mechanical strength of the composite boards, allowing the composite boards to support additional loading beyond the point when the first cracks had been initiated within the composite boards. Furthermore, the presence of the CC powder as filler material also contributed to increasing the deflection response of the composite boards as observed in the composite samples K10-CC1, K10-CC2 and K10-CC3 with a deflection peaking at approximately 0.75 mm compared to the reference sample K10 whose deflection peaked at approximately 0.5 mm. However, it was observed that when 4% CC powder was incorporated into the composite board, a reduction in the flexural strength as well as the deflection response was noted. Therefore, this research suggested that a maximum of 2% CC powder should be safe for incorporation into cement composite boards without negatively affecting the mechanical performance of the composite boards.

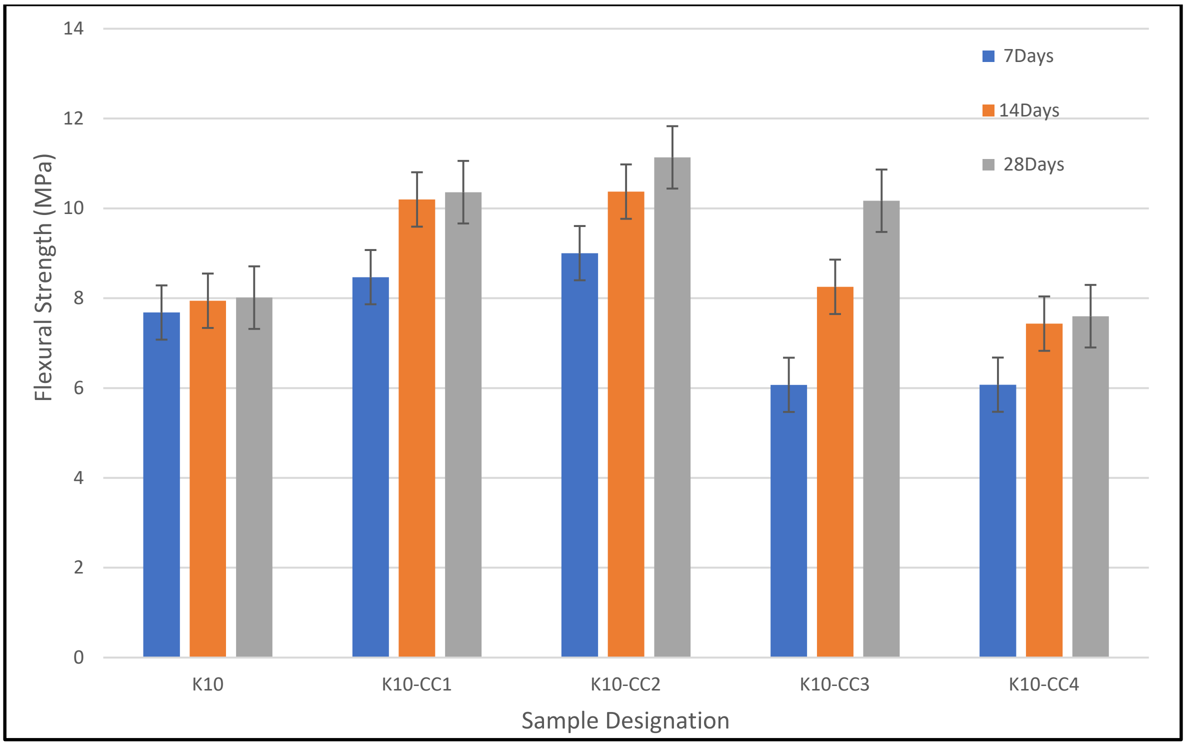


Fig. 10 Flexural Strength of FCB Reinforced with 10 wt.% Kraft Pulp Fibre and 1-4% CC Powder as Filler Material

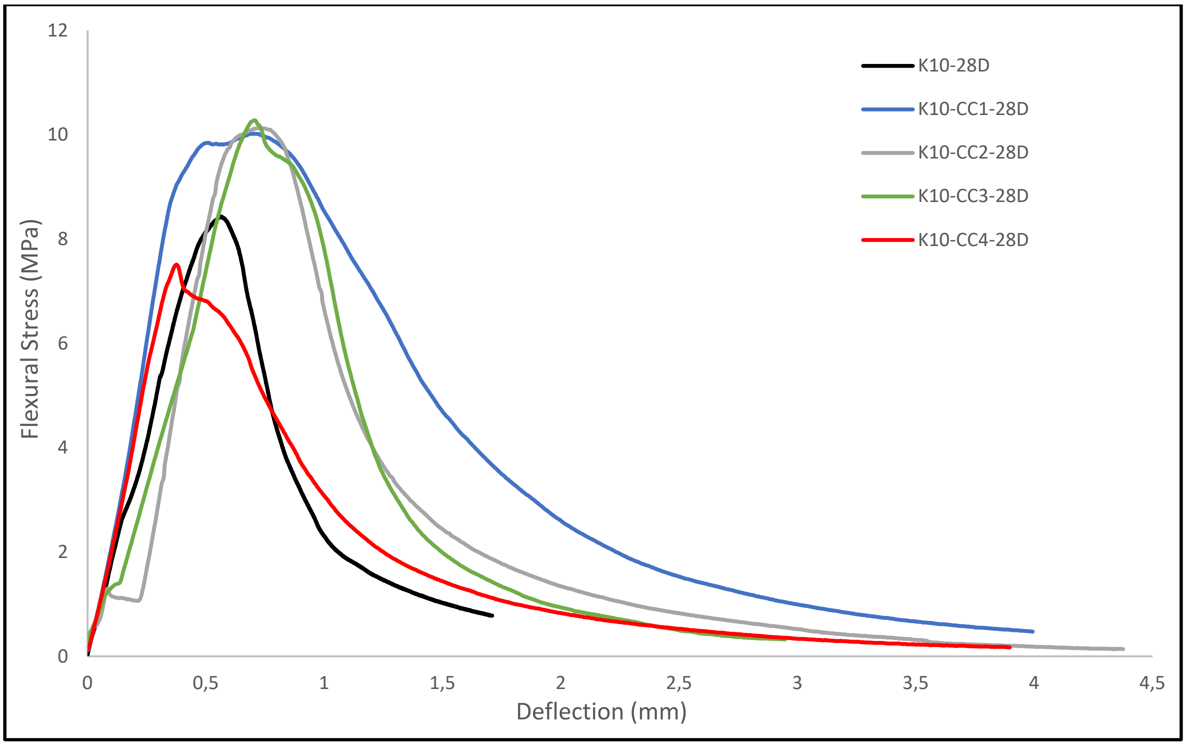


Fig. 11 Flexural Behaviour of FCB Reinforced with 10 wt.% Kraft Pulp Fibre and 1-4% CC Powder as Filler Material

C. SEM Morphology of the Fractured Surfaces of Cement Composites Boards

The fractured surface morphology of the composite boards reinforced with 4 wt.%, 8 wt.%, 10 wt.%, and 20 wt.% kraft pulp fibre is presented in Figs. 12 (a) and (d), respectively. From the SEM image in Fig. 12 (a), it was observed that the reinforcing kraft pulp fibre was sparingly, though uniformly distributed within the composite board. There was still the appearance of some locations with little to no fibre reinforcement. A similar situation is observed in the SEM image of Fig. 12 (b). Although, the presence of the reinforcing kraft pulp fibres becomes more conspicuous due to the increase in the kraft pulp fibre reinforcement. Furthermore, in the SEM micrograph shown in Fig. 12 (c), a more pronounced effect of the reinforcing kraft pulp fibre could be seen combined with uniform distribution and effective bonding at the fibre-matrix interface. This could be the reason behind the maximum mechanical strength displayed by this composite sample as previously explained and illustrated in Fig. 8. However, in the SEM morphology depicted in Fig. 12 (d), the presence of fibre agglomeration or balling effect, as well as fibre pull-out, could be seen in the SEM morphology of the composite board containing 20 wt.% kraft pulp fibre as reinforcement. The balling effect was caused by the excess fibre clumping, hence, forming weak points within the composite boards, which resulted in the loss of mechanical strength, illustrated in Fig. 8.

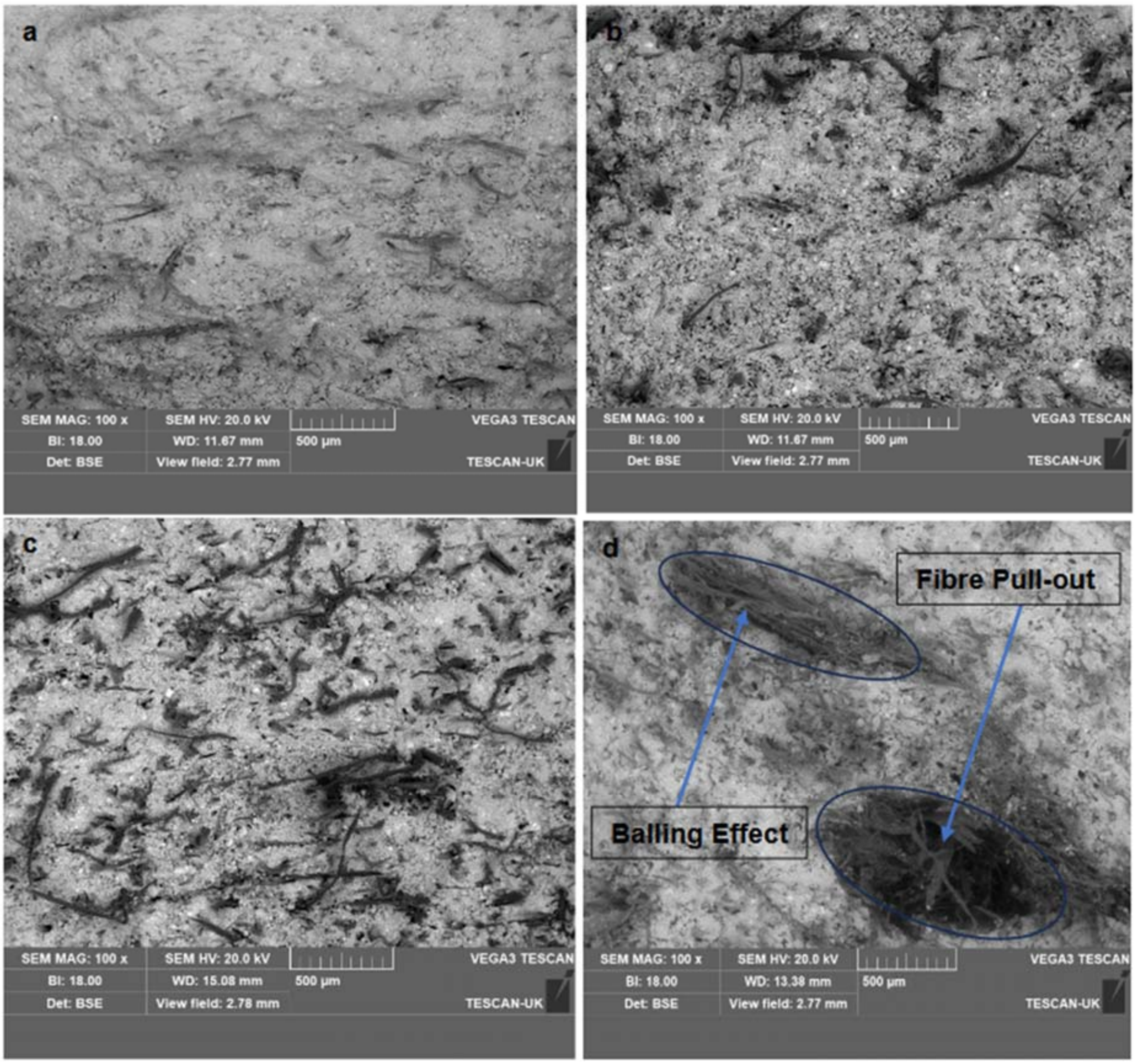


Fig. 12 SEM of Fractured Surfaces of (a) K4-28D, (b) K8-28D, (c) K10-28D, (d) K20-28D

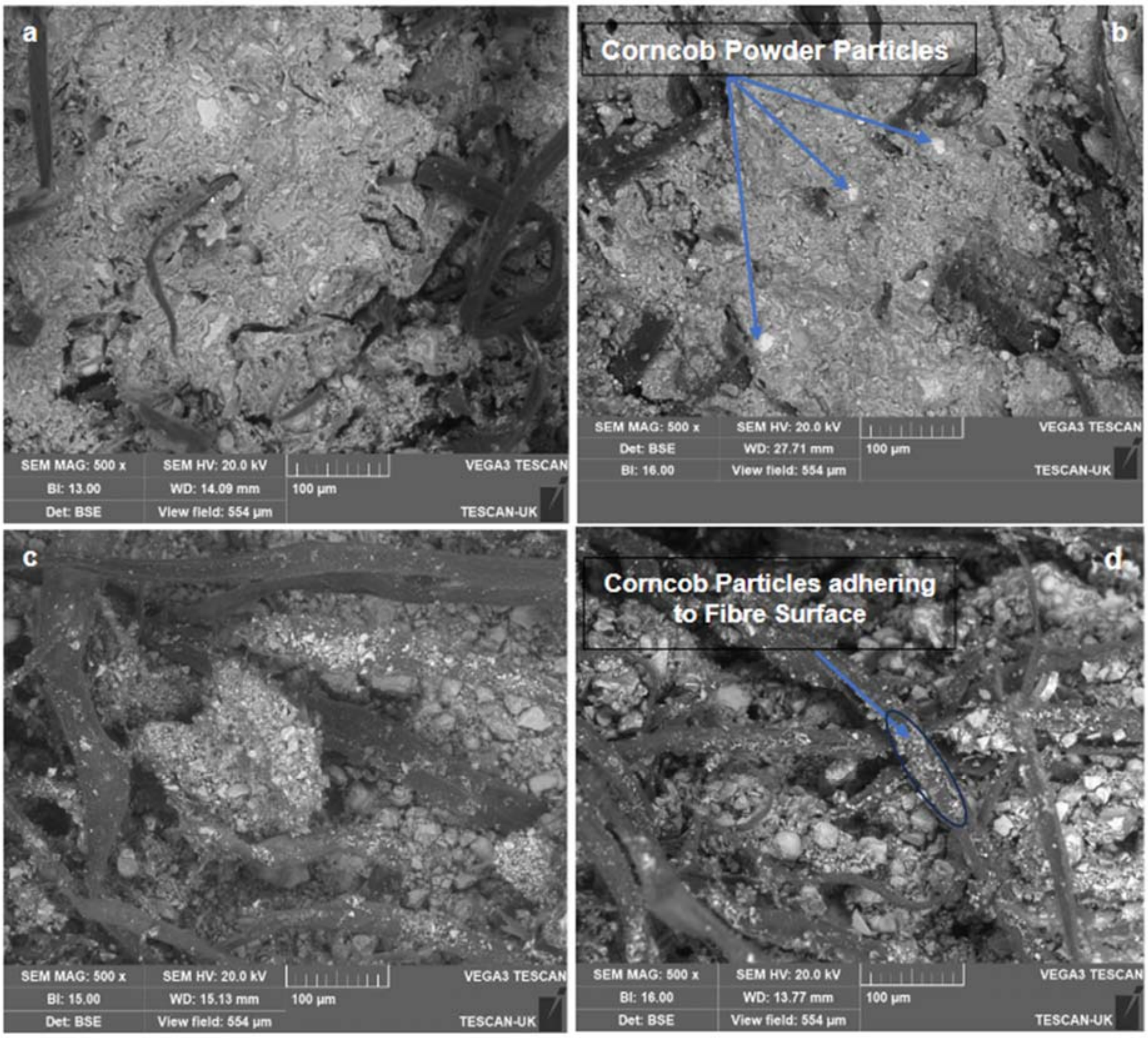


Fig. 13 SEM of Fractured Surfaces of (a) K10-CC1, (b) K10-CC2, (c) K10-CC3, (d) K10-CC4

Figs. 13 (a) and (d) present the SEM of the fractured surfaces of composite boards reinforced with 10 wt.% kraft pulp fibre incorporating 1%, 2%, 3%, and 4% CC powder particles as filler materials respectively. In Fig. 13 (a), which depicts the composite board containing 1% CC powder as filler materials, the presence of the CC powder was not very obvious due to the lower percentage. However, its filler effect could be noticed through the improvement in the flexural strength of the composite board as compared to the reference sample without CC powder addition. Fig. 13 (b) depicts the composite board containing 2% CC powder as filler material. Here, the presence as well as the filler effect of the CC powder becomes very evident. The CC powder particles could be seen filling the voids within the cement matrix, thereby reducing porosity and enhancing the microstructural compactness of the composite board. This results in an increase in the mechanical strength of the composite board as recorded in Fig. 10. On the other hand, it was observed in Figs. 13 (c) and (d) which depict the composite boards containing 3% and 4% CC powder as filler materials respectively, that the presence of the CC powder constitutes a nuisance within the composite boards due to the higher volume. This higher percentage makes the CC powder adhere to the surfaces of the reinforcing fibres causing an interference in the mechanical bonding between the fibre and the cement-matrix, thus reducing the effectiveness of bonding at the fibre-matrix interface, leading to a reduction in the strength of the composite board as seen in Fig. 10.

IV. Conclusion

The current research explores the possibility of using agro-waste CC powder as a filler material, reducing cement content, and improving the properties of kraft fibre-reinforced cement composites. The study examined the mechanical and morphological properties of the developed cement composite boards and concluded as follows:

- Kraft pulp fibres obtained from recycled waste cardboard papers can be re-used as processing and reinforcing fibres in cement composite boards that are suitable for use in low-cost building construction applications.
- The appropriate amount of kraft pulp fibres required to achieve optimum mechanical strength and ductility in the

composite boards is 10 wt.% of the composite composition.

- Based on the findings from this study, the optimum percentages of CC powder as filler materials that contributed to enhancing the mechanical properties of the cement composite board is 1-2% of the mass of the matrix material.
- CC which is currently discarded as agricultural waste residue can be suitable processed to obtain CC powder which can be used as filler materials to reduce cement contents and improve the strength performance of cement composite boards. By incorporating this agricultural waste into cement composite boards, the environmental impact of construction materials can be reduced. Thus, the use of agro-waste fibres in construction materials contributes to a circular economy and reduces the demand for non-renewable resources.
- CC as an agricultural waste product is abundantly available and generally inexpensive. Therefore, using it as a filler material can reduce the cost of raw materials in cement board production, making the composite board more economically viable.

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